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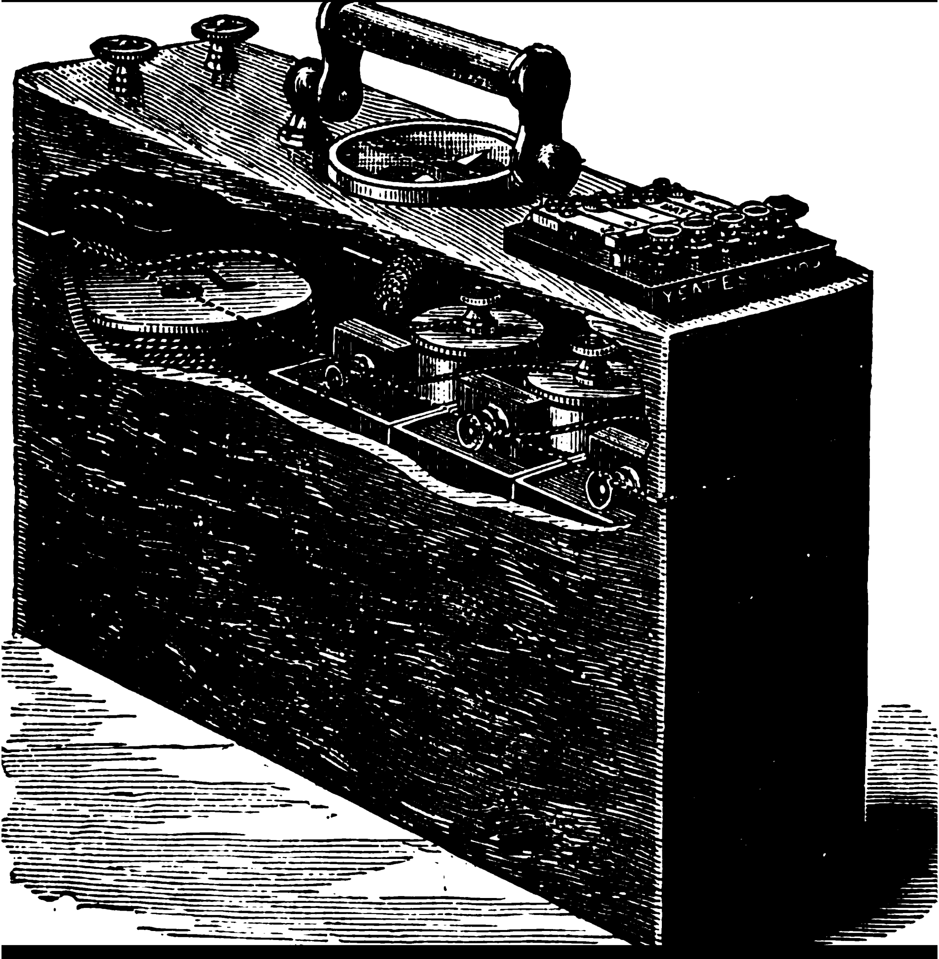

Boiler and factory chimneys

Robert Wilson

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TABLE OF DIMENSIONS OF CHIMNEYS.

On the basis of the head of outside air being equal to half the height of Chimney, and the flues being not much over six times the length of boiler.

Height of Chimney in feet.	$W = \frac{A\sqrt{H}}{\cdot07}$ = lbs. of coal per hour per 1 foot of area at top of Chimney.	$H_0 = 0{\cdot}192\,H^{\frac{4}{5}}\,(\cdot0761)$ = height in inches of column of water balanced by draught pressure.	$HP = \frac{A\sqrt{H}}{\cdot75}$ = Horse power of each sq. ft. of Chimney. Assuming 7 lbs. of coal per horse power.	$A = \frac{\cdot8}{\sqrt{H}}$ = area of top of Chimney in feet per H.P. for 1 or 2 boilers.	$A = \frac{\cdot5}{\sqrt{H}}$ = area of top of Chimney in ft. per H.P. where several boilers are working together.	$A = \frac{1\cdot}{\sqrt{H}}$ = area of flue in feet per horse power.
30	78·24	·218	7·3	·146	·091	·182
40	90·35	·296	8·4	·126	·077	·155
50	101·01	·364	9·4	·113	·070	·140
60	110·65	·437	10·3	·103	·064	·129
70	119·52	·5	11·2	·095	·059	·119
80	127·77	·58	11·9	·089	·055	·111
90	135·52	·656	12·6	·084	·052	·105
100	142·85	·729	13·3	·08	·05	·01
125	159·71	·911	14·9	·071	·044	·089
150	174·96	1·09	16·3	·065	·04	·082
175	188·98	1·26	17·6	·060	·038	·075
200	202·03	1·45	18·8	·056	·035	·07
225	214·28	1·64	20	·053	·033	·066
250	225·87	1·82	21	·05	·031	·063
275	236·90	1·99	22	·048	·03	·06
300	247·43	2·18	23	·046	·028	·057

When the area at top is given as in fifth and sixth columns, the dimension of the side of square in a square chimney can easily be found by taking the square root of the area, or side of square $= \sqrt{A}$, and the diameter for a round chimney $= \sqrt{\frac{A}{\cdot7854}}$. See p. 30.

BOILER AND FACTORY CHIMNEYS,

THEIR DRAUGHT-POWER AND STABILITY:

WITH A CHAPTER ON

LIGHTNING CONDUCTORS.

BY

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PREFACE.

The following Chapters were commenced with the intention of adding them to the 5th Edition of my "Treatise on Steam Boilers," in consequence of having had numerous enquiries respecting the proper size of chimney for boiler-work. The information is, however, likely to be more useful in its present form, hence the appearance of this little book.

I had some diffidence in calling in question the correctness of the theory of draught adopted by Rankine, by Morin, and by Peclet in the 2nd Edition of his "Traité de la Chaleur," but after going to press I find that Peclet in the 3rd Edition of his work has altered his theory and adopted the same as I have arrived at.

ROBERT WILSON.

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BOILER AND FACTORY CHIMNEYS.

CHAPTER I.

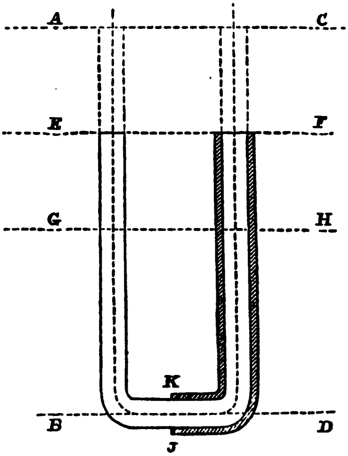
CHIMNEY DRAUGHT.

BOILER chimneys are used not only in order to obtain a sufficient flow of air to maintain a steady combustion, but also to discharge the noxious gases of combustion at such a height above the ground that they shall not be considered a nuisance.

It is well known that the pressure of a fluid is equal in all directions, and is measured at any given point by the area, density, and height above that point of the column of liquid or gas which exerts the pressure.

In fig. 1, let $AB = CD$ represent the height of the atmosphere, and DF the height of a chimney. Then the pressure on the top of the column of air in the chimney is measured by CF, and the pressure on the bottom of the same column by $CF + FD$. When the temperature and density of the column FD inside the chimney are the same as those of a column EB of equal height and area outside, it is evident that the two columns $AE + EB$ and $CF + FD$ will be in equilibrio, and there will be no tendency to produce motion. Should, however, the column FD inside the chimney be of a higher temperature and consequently of less density than a column EB of equal height and area outside, the weight of the column *A E* + *E B* will be greater than that of *C F* + *F D*, whence the preponderating pressure at *J K* will force the inside column *F D* upwards. If the air, as it passes *J K*, becomes heated, and the diminished density of the column inside the chimney is maintained, the column will continue to be forced upwards by the unbalanced pressure outside.

Fig. 1.



This is what takes place when a fire is lighted under a chimney, and the continuous current of cold air, that forces the heated and lighter air upwards, produces what is called the draught, which is the name given (wrongly) to the quantity of heated gas discharged by the chimney, whether expressed by weight or volume of the gases; or the velocity of the current; or by the pressure required to produce that current. It is evident that the force of the draught will depend upon the difference in the weight of the two columns *A E* + *E B* and *C F* + *F D*. Now as *A E* and *C F*, the height of the portions of the columns above the chimney, are equal, they balance each other, and may be left out of consideration for the present.

Assuming the temperature of the atmosphere to be 62°—a fair average—then every additional degree of heat imparted to the air would increase its bulk $\frac{1}{523}$ or, by increasing its temperature by 523 degrees, its volume would be doubled, and its density consequently reduced by one-half.

Let D = 0·0761, the density or weight of a cubic foot of the outside air at 62°;
d = the density of the hot gas in the chimney, assumed to be constant from the bridge to the chimney-top;
t = the temperature of the hot gas in the chimney;

then the density d of the hot gas at any required temperature t, can be found by the formula

$$d = \cdot 0761 \left(\frac{523}{461 + t}\right).$$

If we represent the weight of the heated column by *D H* in fig. 1, *F H* = *E G* will represent the difference in weight or pressure between the two columns *F D* and *E B*.

Let H = the height of the chimney;
P = the difference in pressure between the two columns;

then $P = H D - H d = H (D - d)$.

This unbalanced pressure P is the motive force which drives the hot-air up the chimney, and the height in feet of a column of the external air or "*head*" H_1 *in feet of cold air*, to produce this pressure, acting by its own weight, is found by dividing P by the density of the external air, whence

$$H_1 = \frac{P}{D} = \frac{H (D - d)}{D}$$

This head H, is represented graphically on fig. 1 by *F H* = *E G*, as before.

If we take, for example, a chimney 90 ft. high, in which the volume of the air is doubled in passing through the fire, we shall have $D = 0{\cdot}0761$ and $d = 0{\cdot}0380$, whence

$$H_1 = 90\left(\frac{{\cdot}0761 - {\cdot}0380}{{\cdot}0761}\right) = 90(\tfrac{1}{2}) = 45 \text{ ft.}$$

The head is proportional to the height of the chimney.

When we know

$t =$ the temperature of the chimney gases above zero;

$T =$ the temperature of the atmosphere;

$a =$ the coefficient of expansion of air for one degree of the thermometer at zero $= 0{\cdot}00217$;

we have

$$H_1 = H\left(\frac{D-d}{D}\right) = a\left(\frac{t-T}{1+a\,t}\right)H.$$

Taking $t_1 =$ the temperature of the gases above that of the atmosphere at 62°, which makes $T = 62°$, we have the following simple rule

$$H_1 = \frac{t_1}{523+t_1}H.$$

Suppose the temperature of the gas inside the chimney to be 600°, then

$t_1 = 600° - 62° = 538°$, and

$H_1 = \dfrac{538}{1061}H = 0{\cdot}574$, or very nearly one half the height of the chimney.

When the head is known, the theoretical mean velocity per second with which the external air tends to enter the chimney can easily be calculated. Supposing the chimney were quite empty, and there were no loss by contraction at entrance, then, if a column of outside air were allowed to descend into it by its own weight, the velocity which the column would acquire by the time its top reached the entrance into the chimney would be that due to the height the column had fallen, which would be equal to the height of the chimney, and the velocity of the entering air would be $= \sqrt{2\,g\,\mathrm{H}} = 8\,\sqrt{\mathrm{H}}$, $2\,g$ being twice the velocity produced by gravity in the first second of fall.

But the chimney is never quite empty, and the height of the column to which the theoretical velocity, v, in feet per second, of the entering cold air is due, becomes equal to the square root of the height of the head H_1 or the theoretical velocity of the cold air,—

$$v = \sqrt{2\,g\,\mathrm{H}\,\frac{\mathrm{D} - d}{\mathrm{D}}} = 8\,\sqrt{\mathrm{H}\,\frac{\mathrm{D} - d}{\mathrm{D}}}$$

$$v = 8\,\sqrt{\mathrm{H}\,a\,\frac{(t - \mathrm{T})}{1 + a\,t}} = 8\,\sqrt{\mathrm{H}\,\frac{t_1}{523 + t_1}}$$

$$= 8\,\sqrt{\mathrm{H}_1}.$$

Suppose the head of cold air $\mathrm{H}_1 = {}^{\cdot}5\ \mathrm{H}$ and $\mathrm{H} = 90$, then $v = 8\sqrt{45} = 53{\cdot}7$.

On passing through the fire the air is increased in *volume* in proportion to the increase of temperature, but not by the amount of the bulk of the gases it enters into combination with (see p. 19). The velocity, therefore, of the heated air will be much greater than that of the entering cold air.

As the velocity of the gases is proportional to their volumes, we have for V, the theoretical velocity of the hot air in the chimney,

$$\mathrm{V} = v\left(\frac{461 + t}{523}\right) = 8\,\sqrt{\mathrm{H}_1}\left(\frac{461 + t}{523}\right) = 8\,\sqrt{\mathrm{H}_1} \times \frac{\mathrm{D}}{d}.$$

Peclet, Rankine, and Morin have all taken the head, in feet of *hot gas*, or $h_1 = H_1 \frac{D}{d}$ and make $V = \sqrt{2\,G\,H\,\frac{D-d}{d}}$. This is evidently an error, since $\sqrt{\frac{D-d}{d}}$ is not equal to $\frac{D}{d}\sqrt{\frac{D-d}{D}}$. The velocity of the hot gases is always dependent in the first place upon the velocity of the entering cold air, and consequently upon H_1 and not upon the head of hot gas h_1.

If $Q =$ volume of gases discharged per second by the chimney;
$A =$ area of chimney; we have

$$Q = V\,A = A\,8\sqrt{H\frac{D-d}{D}} \times \frac{D}{d} = A\,8\sqrt{H_1} \times \frac{D}{d}$$

$$= A\,8\sqrt{H\,a\,\frac{(t-T)}{1+a\,t}} \times \frac{461+t}{523.}$$

From the foregoing it is evident that the theoretical velocity and volume of the hot gas discharged from the chimney are proportional to *the square root of the height of the chimney; to the square root of the head or excess of pressure of the outside air over that of the hot gas in the chimney;* or to the square root of the increase of temperature of the hot gas.

An error made by some writers on this subject is in assuming that because $V = \frac{D}{d}v$ the draught force increases in proportion to the increase in velocity or inversely as the increase in density of the heated gases. But as the motive force, or force that produces the draught, is proportional to the height of the head, and the velocity due to this head is proportional to the square root of its height or to $\sqrt{H_1}$, and as this height is proportional to the ratio of the densities, or to $\frac{D-d}{D}$ we have the velocity proportionate to $\sqrt{\frac{D-d}{D}}$ and not to $\frac{D}{d}$.

The actual velocity of the entering cold air and hot gases is reduced below the theoretical velocity by the resistance to their passage offered by the contracted areas through the fire-grate and layer of fuel, and over the bridge, by the bends and change of direction in the flues, by the change of shape and area of flues which cause eddies in the current, and by the friction against the sides of the flues and chimney.

Let $\frac{1}{K}$ express the relation of these various resistances to the velocity of the hot gases, then we shall have

$$V=\frac{1}{K}\sqrt{2\,G\,H_1\times\frac{D}{d}}.$$

According to Peclet's researches the actual velocity is given approximately by the following formula.

$$V = 8\left(\frac{461+t}{523}\right)\sqrt{\frac{H_1}{1+G+\left(\frac{f\,l}{4}+N\right)\left(1+a\,t\right)^2}}$$

here l=the whole length of chimney and flues, in feet;

f=a co-efficient of friction which Peclet found to be 0·012 for the passage of furnace gases over sooty surfaces;

d=diameter of round, or side of square flues;

G=a factor of resistance for the passage of air through the grate and the layer of fuel above it, which may be taken at 40 for ordinary Boiler furnaces.

N = number of bends at right angles to direction of current.

Morin, who has wrongly, as we consider, assumed the velocity of the hot gas to vary as $\sqrt{\frac{D-d}{d}}$ instead of $\sqrt{\frac{D-d}{D} \times \frac{D}{d}}$, gives the following method of investigating the forms of resistance theoretically, the co-efficients being our own:—It is evident that the moving force P, which tends to make the air enter the chimney is expressed by

$$P = (D-d) A H$$

A being the area of the chimney as before. If the mean velocity of the current in the chimney be V, the work developed per second by the motive pressure will be

$$(D-d) A H V.$$

The resistance of the sides to the movement of the gases will be represented by the expression

$$\frac{d S L \beta V^2}{g}.$$

S being the perimeter, or contour of the flues or chimney; L, the length of the chimney and flues, being equal to H when vertical; β, a co-efficient for any given kind of internal surface of flues and chimney.

The work developed per second by this resistance will be

$$\frac{d S L \beta V^3}{g}.$$

If $M = \frac{W}{g}$ the mass of the gases, whose weight $W = d A V$, the *vis viva* imparted to this mass by the difference of pressures or motive force P will be

$$M V^2$$

Now this *vis viva* is usually diminished in at least six different modes:—

1. By the contraction at the entrance of the ash-pit. Now, supposing this entrance to be equal in area to the flues, the loss of *vis viva* may be expressed by

$$M\left(\frac{1}{m}-1\right)^2 V^2$$

m being the co-efficient of contraction at entrance. This loss of *vis viva* may be neglected when the orifice of entrance is such that m differs very little from unity; but this is seldom the case. The co-efficient m of contraction is usually taken from 0·60 to 0·80. Taking it at 0·70, we have

$$\left(\frac{1}{m}-1\right)^2 = \left(\frac{1}{\cdot 70}-1\right)^2 = \cdot 185.$$

The total *vis viva* given to the gases in motion, and which consists of that maintained in the chimney and of that lost at the entrance, will be expressed by

$$M\left(+ \left(\frac{1}{m}-1\right)^2\right) V^2$$

2. If the area of the entrance orifice has a section different from and less than that of the flues or chimney, the loss of *vis viva* will be $M\ (V'-V)^2 = M\ V^2\left(\frac{A}{m' A'}-1\right)^2$, V' being the velocity through the orifice whose area is A'.

The term $\left(\frac{A}{m' A'}-1\right)^2$ may acquire a considerable value when all the air has to pass through the bars and bed of fuel and over the bridge. The area for the passage of air being frequently only $\frac{1}{10}$ the area of the section A of the chimney (or less when a thick layer of caking coal is used), in this case

$$\frac{A}{m' A'} = 10$$

and

$$\left(\frac{A}{m' A'} - 1\right)^2 = 81.$$

When the area for the passage of air through the fuel equals the space between the fire bars or commonly ½ the section of chimney outlet, then

$$\frac{A}{m' A'} = 2$$

and

$$\left(\frac{A}{m' A'} - 1\right)^2 = 1.$$

This formula is, strictly speaking, only applicable where the density of the fluid does not change in its passage.

3. A loss of *vis viva* takes place at every elbow or bend. With a single flush-flued externally fired boiler there may be only a single elbow, namely at the bottom of the chimney; but in tubular boilers set in the best manner and connected with a single chimney there are often as many as eight elbows. Taking this number, and expressing the loss at each bend by $M\left(\frac{1}{m''} - 1\right)^2 V^2$ we have to repeat the term $\left(\frac{1}{m} - 1\right)^2$ eight times. Supposing $m'' = 0{\cdot}70$, we have

$$8\left(\frac{1}{m''} - 1\right)^2 = 8\left(\frac{1}{\cdot 70} - 1\right)^2 = 1{\cdot}48.$$

A similar loss occurs where two or more currents meet us in a split draught, uniting again in a single flue.

4. Then we have the loss of each enlargement of the

flue represented by $M\left(1-\frac{A}{0}\right)^2 V^2$. This nearly always occurs at the bridge, at the entrance of the flues into the chimney, and where a number of tubes deliver into a large space or flue. The greatest value this term can have is in the case where the area 0 of the enlarged section is so large in proportion to that A of the small flue, or tube, that we may regard $\frac{A}{0}=0$. Then

$$\left(1-\frac{A}{0}\right)^2=1.$$

Supposing $\frac{A}{0}=\frac{1}{2}$ then

$$\left(1-\frac{A}{0}\right)^2=0·25.$$

5. When the area A_1 of the exit orifice of the chimney is less than the area A, the velocity will be V_1 instead of V making the co-efficient of contraction m_1 the volume of the gases discharged will be

$$m_1 A_1 V_1 = A V,$$

$$\text{whence } V_1 = \frac{A}{m_1 A_1} V.$$

when m_1 A_1 is less than A_1 the velocity V will be greater than V, which will give a greater steadiness of draught but diminish the volume discharged per second. Taking the velocity of exit orifice to that of mean velocity as 3 to 2, we have $V_1 = \frac{3}{2} V = 1·5\ V$,

$$\text{whence } \left(\frac{A}{m_1 A_1}\right)^2 = 2·25.$$

In tapered boiler chimneys the area A is usually taken as that of the outlet, and in such cases the *vis* *viva* becomes $M\ V_1^2$ instead of $M\ V^2$, and is not the average velocity of the draught in the chimney.

6. The resistance arising from the friction of the air or gases over the sooty surface of the flues and chimney will be represented by $\frac{2\ S\ L\ \beta}{A}$ as already given.

In a circular or square chimney we have $\frac{S}{A} = \frac{4}{D}$ this term then becomes

$$\frac{8\ L\ \beta}{D}$$

The value of the co-efficient β depends upon the number and shape of tubes, flues and passages through which the gases flow, and is given by Peclet as 0·012 for sooty surfaces.

The proportion $\frac{L}{D}$ varies very much, taking it at 100 and 30 respectively, the term $\frac{8\ L\ \beta}{D}$ becomes

$$8 \times 100 \times {\cdot}012 = 9{\cdot}6.$$
$$8 \times 30 \times {\cdot}012 = 2{\cdot}880.$$

Collecting these terms we have :—

1st term	$\left(\frac{1}{m} - 1\right)^2$	=	1·85	1·85.
2nd ,,	$\left(\frac{A}{m'\ A'} - 1\right)^2$	=	1	81
3rd ,,	$\left(\frac{1}{m''} - 1\right)^2 \times 8$	=	1·48	1·48.
4th ,,	$\left(1 - \frac{A}{0}\right)^2$	=	·25	·25.
5th ,,	$\left(\frac{A}{m_1\ A_1}\right)^2$	=	2·25	2·25.
6th ,,	$\frac{2\ S\ L\ \beta}{A}$	=	2·88	9·64.
			9·71	96·47.

When all these causes of loss of *vis viva*, or motive force, are present in the same draught the principle of *vis viva* applied to this circulation will give us the following relation :—

$$MV_1^2 + M\left(\frac{1}{m} - 1\right)^2 V^2 + M\left(\frac{A}{m'A'} - 1\right)^2 V^2 + M\left(\frac{1}{m''} - 1\right)^2 V^2$$
$$+ M\left(1 - \frac{A}{0}\right) V = 2(D - d) A H V - \frac{2 d S L \beta V^3}{g.}$$

In this general equation, the mass of air which passes each section in one second is the same, and in the expression of its value

$$M = \frac{d A V}{g}$$

whence

$$\frac{d V}{g} = \frac{M}{A.}$$

Also according to the notation already employed

$$V_1 = \frac{A}{m_1 A_1} V$$

dividing both sides of the general equation by

$$M = \frac{d A V}{g}$$

we have the following,

$$V^2 \left\{ \left(\frac{A}{m_1 A_1}\right)^2 + \left(\frac{1}{m} - 1\right)^2 + \left(\frac{A}{m'A'} - 1\right)^2 + \left(\frac{1}{m''} - 1\right)^2 + \left(1 - \frac{A}{0}\right)^2 \right.$$
$$\left. + \frac{2 S L \beta}{A} \right\}$$
$$= 2 g \left(\frac{D - d}{d}\right) H = 2 g \frac{a(t - T) H}{1 + a T}$$

whence

$$V = \sqrt{\frac{2 g \left(\frac{D - d}{d}\right) H}{\left(\frac{A}{m_1 A_1}\right)^2 + \left(\frac{1}{m} - 1\right)^2 + \left(\frac{A}{m'A'} - 1\right)^2 + \left(\frac{1}{m''} - 1\right)^2 + \left(1 - \frac{A}{0}\right)^2 + \frac{2 S L \beta}{A.}}}$$

or

$$V = \sqrt{\frac{2g\,\frac{a\,(t - T)\,H}{1 + a T}}{\left(\frac{A}{m_1 A_1}\right)^2 + \left(\frac{1}{m} - 1\right)^2 + \left(\frac{A}{m' A'} - 1\right)^2 + \left(\frac{1}{m''} - 1\right)^2 + \left(1 - \frac{A}{0}\right)^2 + \frac{2\,S\,L\,\beta}{A.}}}$$

Substituting for the denominator in this equation the values found for each term we have for the first

$$V = \sqrt{\frac{2g\left(\frac{D - d}{d}\right)H}{9{\cdot}71}} = 0{\cdot}3\sqrt{2g\left(\frac{D - d}{d}\right)H}\,;$$

and for the second value,

$$V = 0{\cdot}102\sqrt{2g\left(\frac{D - d}{d}\right)H.}$$

From the results of observation and experience it may be safely considered that the velocity as a rule lies between those given by using the two co-efficients 0·1 and 0·3. For ordinary practice, where there are not many very small tubes or very restricted passages over the bridge and elsewhere, and where the fire is not very thick and solid the co-efficient 0·3 may be used. Then

$$V = {\cdot}3\sqrt{2g\left(\frac{D - d}{d}\,H\right.}$$

$$V = 2{\cdot}4\sqrt{\frac{D - d}{d}\,H.}$$

In practice with a strong draught $\sqrt{\frac{D - d}{d}}$ differs very slightly from unity and may be left out, whence we have

$$V = 2{\cdot}4\sqrt{H.}$$

In using the correct formula $V \sqrt{\frac{D-d}{D}} H \times \frac{D}{d}$ we should have found that for the conditions of density, &c., usually found with boiler chimneys that $\sqrt{\frac{D-d}{D}} \times \frac{D}{d}$ is usually about 1·4 where $\sqrt{\frac{D-d}{d}} = 1$, whence we should have $V = 1{\cdot}7 \sqrt{\frac{D-d.}{D}} \times \frac{D}{d}$. Where the length of the horizontal flues is great compared with that of the chimney and their diameter small, the velocity will be somewhat diminished.

With respect to the expression

$$\frac{D-d}{d} = a\left(\frac{t-T}{1+aT}\right)$$

Morin states that Peclet, in his "Traité de la Chaleur," 3rd ed., (p. 37, vol. i.,) has admitted

$$\frac{D-d}{d} = a\frac{(t-T)}{1+at}$$

an error which in many cases may materially alter the results, since the temperature T of the atmosphere scarcely ever varies more in this country than from 10° to 80°, making the denominator $1 + aT$, vary from 1·02 to 1·16, whilst the other denominator, $1 + at$, would vary from 1·2 to 2·3, and lead to very material mistakes. This, however, does not apply practically to boiler chimney draughts.

In the above mode of investigating the motive force of the draught it would have been more correct to have taken the *vis viva* of the cold air entering the ash-pit and fire-bars at the velocity due to its density, and to have made allowance for the change in the density as the air passed through the fire. It may be here remarked that theoretical and scientific refinements are unnecessary and often worse than useless in seeking to determine the actual velocity of the draught of any given chimney, when the circumstances and conditions are so complex and uncertain in actual practice that no theoretical formulæ can be expected to give results even approximately correct under all circumstances and conditions of working, which are continually varying. It is needless to seek to determine the exact pressures or densities at the top and bottom of the chimney in order to arrive at the average pressure and density at a given barometrical pressure when this pressure varies from day to day. The direction of the wind has a very decided effect upon the draught; when it blows strongly into the ash-pit and furnace it may greatly increase, and when it blows from the ash-pit it may greatly lessen, the motive force of the preponderating column of cold air. Then the shape of the chimney top, hygrometric condition of the atmosphere, presence of blow-holes or leakages in brickwork, angle or inclination to each other of bends at converging flues and points of uniting of split draughts, partial choking up of air passages and flues by clinkers, soot, and flue dirt, change in the quality of fuel, and many other uncertain circumstances likely to influence the force of the draught, are more important than smoothness of brickwork and any accurate determination of mean temperatures and densities. It is, however, well to know that uncertain conditions do exist, in order that we may know pretty nearly how far we may be guided by any rules we may find or establish for our own use.

In examining the general equation (pp. 7 and 13) we gather from the numerator with certainty :—

1st. That the velocity of the air and gases is proportionate to the square root of the height of the chimney, so that by doubling the height the theoretical velocity is increased only in the proportion of $\sqrt{1}$ to $\sqrt{2}$, or as 1 to 1·4, and in seeking to increase the draught by altering the height of the chimney we must quadruple the height in order to double the force of the draught, assuming that the area remains the same and that the additional height causes no more friction, which is, however, not the case, as the increase of height increases the value of the last terms in the denominator, in the equation in p. 7. In practice there is a limit to the height for the best draught, beyond which the additional height increases the resistance due to the increased velocity and friction more rapidly than the flow of cold air. For chimneys not over 3′ 6″ diam. at top this maximum height appears to be about 300ft.

2nd. That the velocity of the flow of cold air is proportionate to the square root of the ratio $\frac{D-d}{D}$. On examining this expression we find that the draught does not increase so quickly as the square root of the difference in temperature between the hot gases and the outside air, and that very little is gained theoretically by increasing the temperature of the gases in the chimney, when the ratio of the densities of the outside air and the hot gas are as 2 to 1. By raising the temperature from 600° to 1200° we should theoretically only increase the draught force in the proportion of ·71 to ·86, and in practice it would be still less.

On the other hand, when we place an economiser in the flue and seek to reduce the temperature of the escaping gases from say 650° to 350°, we should diminish the velocity of the draught only in the proportion of $\sqrt{\cdot 75}$ to $\sqrt{\cdot 61}$, or as 1 is to 0·8.

3rd. From the denominator we gather that the velocity is inversely proportionate to the square root of a denominator in which at least six uncertain elements may combine to make its value equal to from 9 to 100, and, as the co-efficient of reduction depends in each case upon given conditions, the particular values should be introduced into the denominator.

The loss from these causes may be obviated

a, by facilitating the entrance of the air into the ash-pit and through the fire-bars and body of fuel, which may be done by making the dimensions of the passages as large as practicable, and making their shape as favourable as possible for the passage of air.

b, by avoiding as much as possible contractions, elbows, sudden bends, and alterations in the direction of the flow of air. Where contractions necessarily occur, there should be no corners left, but the contraction should be approached gradually by tapering the flue.

c, by avoiding as much as possible all enlargements, and especially sudden enlargements, in the flues, which cause eddies in the current of gases. Here again the flue should be tapered.

d, by making the surface of the masonry as smooth as possible.

e, by having no holes in the brickwork for the cold air to enter. Defects in the brickwork between two parts of a flue, by allowing the hot gases to make a shorter circuit to the chimney, will improve the draught at a sacrifice of economy, as the defective brickwork beneath the boiler practically reduces the extent of heating surface.

In estimating the volume of the gases of combustion, we can take the volume of the mixed carbonic acid, nitrogen, and unburnt oxygen, in the chimney, as equal to the original volume of air, and the density is increased simply in the ratio of the sum of the weights of the air and of the carbon taken up, to the weight of air. The volume of the mixed steam, nitrogen, and unburnt oxygen, is greater than the original volume of air by an amount equal to the quantity of oxygen that has combined with hydrogen, but the quantity of hydrogen in ordinary fuel bears so small a proportion to the total weight of fuel that it is not worth considering, and the volume of the gases in the chimney may be taken as equal to the volume of air at the given temperature.

Then the variation of density produced by the deviation of pressure from the mean atmospheric pressure may be disregarded.

The volume of the gas at 62° and at one atmosphere may be taken as being sufficiently near for all practical purposes at 13 cubic feet for each lb. of air supplied to the furnace.

It has been shown in the author's "Treatise on Steam Boilers," p. 254, that a larger quantity of air than the theoretical amount for combustion passes the furnace, and the following are approximately the quantities of air required under different circumstances.

		Vol. of air at 62° per lb. of fuel.
12 lbs. per lb. of fuel	=	158
18 ,, ,,	=	236
21 ,, ,,	=	275
24 ,, ,,	=	306

The volume Q at any other temperature, *t*, may be found by the formula.

$$Q = Q_1 \frac{(461 + t)}{523}$$

Q_1 being the volume at 62°.

Supply of Air in lbs. per lb. of Fuel.

	12	18	21	24
Temperature.	Volume of gases per lb. of fuel in cubic feet.			
32°	148	222	259	297
62°	158	236	275	316
75°	162	242	282	324
98°	169	252	294	338
212°	204	304	355	408
300°	230	343	400	460
400°	260	388	452	520
500°	290	433	505	580
600°	320	480	558	640
700°	350	524	610	700
800°	380	570	663	760
1200°	500	748	871	1002
2000°	742	1109	1292	1485
2500°	894	1336	1556	1789
3000°	1044	1569	1818	2089
4000°	1346	2011	2343	2692

Let W = the weight in lb. of fuel burnt *per second.*

Q_1 = volume at 62° of air supplied per lb. of fuel (see table).

A = sectional area of chimney in square feet.

Then V the velocity per second of the current in the chimney will be

$$V = \frac{W Q (461 \cdot 2 + t)}{A \times 523}$$

$$W = \frac{V A \times 523}{Q (461 + t)}.$$

From this the weight of fuel per hour that can be burnt in the furnace can be calculated when we have found the velocity, V, by formula

$$V = 2 \cdot 4 \sqrt{H}$$

The density, *d*, of the current in lb. per cubic feet is approximately

$$d = \frac{523}{461 + t} \cdot 0761 + \frac{1}{Q};$$

$$\text{that is, from } 0 \cdot 079\left(\frac{523.}{461 + t}\right) \text{ to } 0 \cdot 082\left(\frac{523}{461 + t}\right).$$

The head, H_1 expressed in feet, of a column of the outside air, may be converted into P_1, an equivalent pressure in lbs. per square foot thus—

$$P_1 = H_1 D = H_1 \times \cdot 0761,$$

the temperature of the atmosphere being taken at 62°.

The unit of head most commonly employed is an inch of water, when syphon water gauges graduated into inches and decimals are used to measure the difference of pressure within and without the shaft. As a cubic foot of water at 62° weighs 62·355 lbs., a column of water one inch high must exert a pressure of 5·2 lbs. per square foot of surface, whence we have $\frac{1}{5 \cdot 2} = 0 \cdot 192$ for a multiplier, and Head in inches of water $= 0 \cdot 192\ P_1 = H_0$

$$H_0 = 0 \cdot 192\, H_1 \times \cdot 0761$$

and

$$H_1 = \frac{\text{Head in inches of water}}{\cdot 192 \times \cdot 0761};$$

from which formula we can calculate the height of chimney to give any required head, expressed in inches of water, when the temperature inside and outside are known:—Since (*p* 4) $H = \frac{\frac{H_1}{t^1}}{323 \times t^1}$ we have

$$H = \frac{\text{Head in inches of water}}{\cdot 192 \times \cdot 0761} \times \frac{523 \times t_1.}{t_1}$$

Suppose we want a chimney sufficiently high to give a head of $\frac{3}{4}$ inch of water, with the temperature inside at 523° above the temperature of the atmosphere we have then

$$H = \frac{\cdot 75}{\cdot 192 \times \cdot 0761} \times \frac{1}{\frac{t^1}{523 \times t_1}} = 103 \text{ feet.}$$

In the expression in Morin's formula for V the velocity of the air which passes up the chimney, it is obvious that this quantity increases indefinitely with the temperature T in the chimney, and it might appear that any increase in the temperature of the hot air would be attended with advantage for increasing the draught. It is not, however, the volume of air, or gases discharged by the chimney that it is desirable to increase, but rather that of the air passing through the grate. Now if we call this volume of the outside air Q_1, and its density D, the weight of air passing through the bars being equal to the weight of that discharged by the chimney, less the amount due to the weight of fuel burnt we have the relation

$$d\,Q = D\,Q_1,$$

whence

$$Q_1 = \frac{d\,Q}{D} = \cdot 95 \frac{1 + a\,T}{1 + a\,t} Q = \cdot 95 \frac{461 + T}{461 + t} Q.$$

Consequently Morin's formula for the volume Q at the temperature t would take the form

$$Q_1 = \frac{d}{D} A \sqrt{2\,G\,H \frac{t - T}{461 + T} \cdot 95}$$

$$= A \sqrt{2\,G\,H\,(461 + T)} \sqrt{\cdot 9 \frac{t - T}{(461 + t)^2}}$$

It is evident from this last form that whilst the weight of air to be discharged increases inversely as the temperature, the draught-force increases as the square root of the temperature, hence the weight of air Q_1 at the temperature T has a maximum value corresponding to a certain temperature t of the gas which is discharged from the chimney, and which should not be exceeded This is found from the factor

$$\sqrt{\frac{-T}{(461+t)^2}}$$

which expression attains a maximum when

$$t=\frac{461+2T}{\cdot 9}.$$

Therefore according to this theory of draught of Morin the best chimney draught takes place when the absolute temperature of the hot gas in the chimney is to that of the external air as $2\frac{1}{7}$ to 1 approximately, or when the head in hot gas $h=H$; that is, when the density of the hot gas is about one-half that of the external air. When the external temperature $T=62°$ we have for the temperature within the chimney $\frac{461\times 124}{\cdot 9}=650$.

Although this result would be modified by taking into account the resistance to the flow of the gases in the long flue between a boiler furnace and the chimney, yet according to this theory, the temperature within any chimney to ensure the best draught should not much exceed 600°, and this limit is completely independent of any disparity in area of flues and chimney, and it is somewhat remarkable that the mean temperature of good boiler chimneys agrees pretty closely with this maximum temperature.

The proper allowance of air for a good chimney draught being about 21lbs. per lb. of fuel, the volume at 62° is about 275 cubic feet per lb. of fuel, and the volume of the hot gas at 600° about 558 cubic feet per lb. of fuel, or 27 cubic feet per lb. of the hot gas itself.

With respect to the head and temperature of the hot gas for the most effective draught, Rankine arrives at a similar result to the above as follows:—the velocity of the gas in the chimney is proportional to $\sqrt{h}$, and therefore to $\sqrt{0{\cdot}96\{461+t-(461+\mathrm{T}.)\}}$ The density of that gas is proportional to $\frac{1}{461+t}$.

The weight discharged per second is proportional to velocity × density, and, therefore, to $\frac{\sqrt{0{\cdot}96\{461+t-(461+\mathrm{T}\}}}{461+t}$; which expression becomes a maximum, when

$$461+t=\frac{2(461+\mathrm{T})}{\cdot 96}=2\tfrac{1}{12}(461+\mathrm{T})\,;$$

therefore the best chimney-draught takes place when the absolute temperature of the gas in the chimney is to that of the external air as 25 to 12.

Morin, in his "Étude sur la Ventilation," treats the hot air in the chimney as not having passed through the fire-bars, which is correct for some modes of ventilation, but not for boiler chimney-draught. He consequently gets the result equivalent to $t = 461 + 2\,\mathrm{T}$, and remarks that Péclet, in the second edition of his Treatise, undertook an investigation for the temperature corresponding to the maximum of the volume of air drawn in by the chimney, and he arrived at the result just given, but the formulæ, which in the third edition of the same work are substituted for those in the second, being inaccurate, led him to suppress the investigation and its consequences, of which there is no longer question, in the third edition.

In what appears to be the correct theory of draught, where $V = \sqrt{2\,G\,H\left(a\frac{t-T}{1+at}\right)} \times \frac{461+t}{523}$, there is no such theoretical maximum temperature for the best draught, as above found by Rankine and Morin, since the velocity and volume of the flow of air increase continually with the increase of temperature t. According to the above expression, based on this theory, as the temperature increases, $\frac{a(t-T)}{1+at}$ approaches nearer and nearer to unity, and if we take the temperature $t = 200$ to $t = \infty$, we shall have the velocity of the cold air varying in the ratio of ·44 to 1, or as 1 to 2·3. As we have already seen at p. 17, when the density of the hot gas is about half that of the density of the outside air, or about 600°, the velocity has ·71 of the theoretical maximum. In practice, however, as the velocity and volume of the gases discharged increase with the rise of temperature, the resistance due to friction increases very rapidly also, and there is a maximum efficiency of draught which is not given by the formula. For boiler furnaces there is no practical gain in the draught, but a great waste of fuel by increasing the temperature of the escaping gases much beyond 600°.

In formula (p. 20) we had

$$W = \frac{V\,A \times 523}{Q\,(461 + t)},$$

whence

$$A = \frac{W\,Q\,(461 + t)}{V\,523},$$

taking the temperature of the discharged gases as 600° and 21 lbs. of air, per lbs. of fuel burnt $\frac{Q\,(461 + t)}{523}$ becomes 558, and

$$A = \frac{W \times 558}{2 \cdot 4 \sqrt{H}}.$$

W is here the weight of coal burnt per second, but taking *w* as the weight burnt per hour, we have

$$A = \frac{w \times 0 \cdot 07.}{\sqrt{H}.}$$

$$w = \frac{A \sqrt{H}}{0 \cdot 07}$$

$$H = \left(\frac{w \times 0 \cdot 07}{A} \right)^2$$

from which we have the column in the table for the area of a chimney to burn a given quantity of coal when the height is given in feet. The area in feet here is taken as that for the top opening of the chimney, and a conical or pyramidal chimney may be treated as though it were cylindrical or parallel. This agrees very nearly with the formulæ commonly given for land chimneys, and answers very well for a single boiler chimney, giving about 2¾ square feet for a Lancashire boiler consuming 10 tons of coal per week of 60 hours with a shaft 90 feet high.

Ninety feet is a very common height for boiler chimneys in large towns, being the minimum height allowed by many Town Improvement Acts, as in Manchester, Leeds, and other towns.

When, however, a number of boilers have only one chimney in common, the area does not require to be so large as the sum of several chimneys used for single boilers, since the friction becomes reduced, and the draught is greatly steadied when several boilers are fired successively, and a higher temperature is maintained.

The flues should be made larger than the area of the chimney, as they become contracted when soot and flue dirt gathers.

A common rule arrived at from experience is to make the flues and area of the chimney top equal to from ⅛th to ⅒th the area of firegrate without taking into account the height of the chimney. Another useful rule is to allow from 2 to 3 square feet for each boiler, having about 30 square feet of firegrate, the former allowance answering for chimneys over 150 feet high, which discharge the gases from several furnaces working together, and the latter for chimneys under 150 feet high, with not over six furnaces. There are many tall chimneys—over 200 feet—answering well with only from 1¼ feet to 1¾ feet square of top opening for every 30 square feet of firegrate where more than half-a-dozen boilers are working together with one chimney in common. It may be taken for granted that ordinary chimneys cannot be too high for obtaining a good draught.

It is usually considered that the larger the area of the chimney the better the draught, but this is not always the case with lofty chimneys where the gases can *cool down too rapidly* in a chimney of large section, and it has been found in several instances that when chimneys are very large for the number of boilers they serve, or for the quantity of coal burnt, as when a chimney is built to serve for future additions to the boiler power, the draught is improved by the better maintenance of temperature as additional boilers are set to work. When the area of the chimney is much larger than the aggregate area of the flues debouching into it, the diminution of friction and the expansion of the hot gases into a large area are favourable for the improvement of the draught. But the velocity of the ascent of the heated gases may be very much diminished, and in extreme cases, where the ascending current does not fill the chimney, so to speak, downward currents of air will be produced, especially with the wind in certain directions, to the impairment of the draught.

The effect of this may be seen in the lazy ascent of smoke from such chimneys, which are usually blackened at the top, and for some distance downwards. In a strong wind the smoke may be seen clinging to the leeward side of the chimney.

On the other hand, if the section be too small in proportion to the aggregate section of flues and fire-grate, the loss of force will be considerable, and can only be slightly increased by increasing the temperature of the escaping gases, which, as a rule, will be adverse to economical fuel consumption.

In practice it is found that with a lower pressure than half an inch of water it is difficult to keep a good fire without continual stirring, which is very wasteful, and produces smoke.

There can be no doubt that in still weather the height of the column of hot gas exceeds that of the chimney when the current of gases ascends beyond the summit, and with certain winds, when the shape of chimney top is favourable, the current of air will tend in many cases to increase the draught beyond that measured by the height of chimney. On the other hand, the shape of chimney-top may be such that the draft may be diminished in high winds, unless the wind blows direct into the ash-pit.

It is also known by experience that with certain states of the atmosphere, although the water-gauge may show a good draught, the fires do not burn briskly, in spite of the quantity of air with which they are supplied. The air appears to be comparatively dead when it blows, especially in the summer, and when it has prevailed from the south. It is not easy to account for this. The direction of the wind is not always a guide, nor indeed can it be expected to be, since it blows in whirls, and may be a south wind in one part of the island and a north wind in another part; yet it is certainly not a characteristic north wind that is found to affect the fires adversely.

The temperature of the escaping gases is usually ascertained by attaching small pieces of the following metals about 1″ long and ¼ inch square to a wire, and introducing them at any desired point in the flues or chimney, the time required to melt them being noted. The melting point of zinc is 700° Fahr.; of lead, 630°; bismuth, 493°; and of tin, 426°. When introduced into the flue behind the damper of Cornish and Lancashire boilers of moderate draught, it has been found that tin melts almost immediately, bismuth in about a minute; lead melts after a short time when the fires are clear, but zinc does not melt under any circumstances. It may therefore be assumed that 600°, or about the melting point of lead, is the average temperature of the escaping gases when the boilers are at work. This shows that the loss of heat is very considerable, and it may be approximately calculated as follows:—Taking the quantity of air used as about 21 lbs. per lb. of fuel, we have (see p. 253 of "Treatise") the weight of the products of combustion of 1 lb. of coal multiplied by the specific heat of the mixed gases = 3·053, and the remaining 9 lbs. of air multiplied by its specific heat ·238 = 2·142. Adding these two products together, we have 5·195, and multiplying 293°, or the elevation of the temperature of the gases above the boiler at 60 lbs. pressure, we have 15320 units of heat, equivalent to 1·5 lbs. of water evaporated per lb. of fuel, or taking the total heat of combustion at 2750° the loss is equal to 10 per cent. compared with the result that would be obtained if the hot gases escaped at the temperature of the boiler.

In the table facing the title-page the sizes of chimneys and flues required for various consumptions of fuel and sizes of boilers are given. In the second column we have the number of lbs. of coal per hour for the consumption of which a chimney of given height and area is suitable. Suppose we have two boilers, each having 35 sq. ft. of grate area, burning 12 lbs. of coal per sq. foot of grate per hour, equal to 840 lbs. of coal per hour, then, by column 2 a chimney 90 feet high should have the area at smallest part about 840 ÷ 135 = 6 sq. feet, that is, about 2 ft. 6 in. square, or 2 ft. 9 in. diam. In columns 4, 5, 6 and 7 the horse-power of different areas of chimney, and the areas for different horse-powers are given. The somewhat meaningless term, horse-power, as usually applied to chimneys, is here reluctantly adopted in deference to the practice which still appears likely to survive a long time in this country, of estimating the capability of boilers by their horse-power.

CHAPTER II.

STABILITY OF CHIMNEYS.

WHEN the proper height and size of chimney have been decided upon to ensure a sufficient draught for the furnace, and also to satisfy the sanitary requirements of the case, the designing with respect to ornamentation, beauty of outline, and harmonising with surrounding buildings, belongs to the architect rather than to the engineer; but the design, so far as the stability of the structure is concerned, still lies within the engineer's province. The principles of stability have been laid down by Professor Rankine, who, up to the time of his death, was regarded as the first authority on this subject.

In estimating the safety and stability of a tall chimney shaft, the strains to be considered are—1st, the pressure exerted by the weight of the masonry or brickwork; and 2nd, the lateral pressure of the wind.

In order to resist the former strain, the best form of structure is that which gives an equal pressure per square unit of area in every section or "bed-joint." Taking, for simplicity, a solid cylinder, the weight evidently increases from the top downwards. This increase of weight must therefore be provided for by an increase in the sectional area as we descend. But this very increase of area augments the rapidity of growth of the mass as we descend, and the sectional area below must be further increased in consequence. For a structure whose centre of figure is the same as its centre of pressure, this law of increase may be deduced with the aid of the differential calculus as follows:—

Let W = weight of top layer of chimney,
A = area of top section,
k = coefficient of safety (for brick say 10 tons per square foot),
c = weight of cubic foot of brickwork,
a = any given section at distance h from the top,
e = basis of natural logs = 2·71828;

then $W = Ak$ or $A = \frac{W}{k}$, which gives us the first sectional area from the top to resist crushing. Any other section can be found by the formula

$$a = A\,e^{\frac{c}{k}h}.$$

$$\text{or } \log a = \log A + 0{\cdot}4343\,\frac{c}{k}h.$$

This formula applies also to hollow cylinders or cones having a straight batter inside.

It is evident from this formula that the outline of the structure will be a logarithmic line, practically straight at the top, and increasing in concavity as it approaches the bottom, giving what is called a "hollow batter." For ordinary chimneys 100 ft. high the amount of concavity required is not worth considering. For tall shafts, 300 ft. high and over, it is sometimes used. There is, however, this great advantage in using a straight batter instead of the theoretically correct hollow batter; viz., the accuracy of the construction can be detected at any stage at a glance of the eye without the aid of instruments. Yet it must be conceded that the hollow batter is much more shapely, and may be worth the extra expense of building.

In a chimney made of blocks of stone or brick separated by plain joints, where there is no lateral pressure, the conditions of stability are—1st, that no joint shall be inclined to the horizon at a greater angle than that of repose, which in this case may be taken at 36½°; and 2nd, that in any given bed-joint the centre of downward pressure, or point which is vertically below the centre of gravity of the superincumbent mass, shall not depart from the centre of figure of the joint more than a certain distance, which for round chimneys may be taken at ¼ the diameter of the joint, and for square chimneys ⅓ the length of the joint.

In order to be able to calculate the strains caused by the lateral pressure of the wind, we must first consider the manner in which the chimney will fail by this pressure.

If the joints between the blocks of the material composing the structure had any tenacity such as the riveted or bolted joints of wrought or cast-iron, or of brick or stone held together by wrought-iron cramps, or by cement of a strength equal to that of the material it joins, the structure should be considered as one piece, and its strength determined by an investigation based on the theory of the strength of materials. But chimneys are usually made of brick or stone, the blocks of which, laid in mortar, touch each other at their joints, which are flat surfaces, held together by pressure and friction, but *not by tension*, so long as the mortar is fresh, and on this basis the stability ought to be considered. Even a year after mixture, the strength of good mortar is only about 50 lbs. per square inch, and a large proportion of failures of chimneys have occurred before the mortar has had time to set, which shows that the strength of the mortar should never be taken into account in designing a new chimney; but for old chimneys the strength of the mortar may also be considered, and taken at 8000 lbs. per square foot when not less than eighteen months old. In cases where chimneys have been sawn to restore them to the perpendicular, and the joints have not been properly remade with mortar or cement, the weight of the chimney can alone be depended upon for its stability.

In designing a new chimney, we may then disregard the tenacity of the mortar, and consider the chimney as being simply set upon its foundation and held down only by its own weight, upon which alone it is dependent for its stability. The moment of stability for a new chimney at any point is evidently half the diameter of the bed-joint, B_1, at this point, × the weight, W, of the chimney above this joint, or $W \times \frac{B}{2}$.

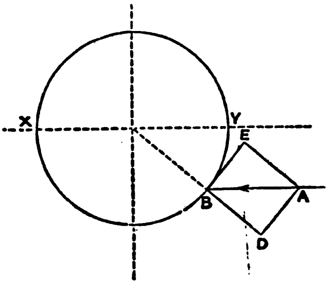
For an old chimney, if we make the solid area in square feet at the joint $= B_1$, we have the moment of stability $= (W + B_1 \times 8000)\ \frac{B}{2}$.

The lateral pressure of the wind may be assumed to act horizontally, and to be of uniform intensity at all heights above the ground. The greatest intensity in this country, against a flat surface directly opposed to it, used to be taken by Rankine at 55 lbs. per square foot, but in 1868 the pressure of the wind at Liverpool was registered at nearly 80 lbs. per square foot, the highest ever known in this country. For new chimneys the pressure of the wind may still be taken at 55 lbs.

The inclination of the surfaces due to the batter or slope of the chimney is usually not sufficient to be taken into account in estimating the pressure of the wind against it.

A circular chimney may be considered as cylindrical in plan, and the total effect of the pressure against the side of a cylinder may be taken as being equal to one-half the total pressure against its diametral plan, or against the side of a square chimney of equal diameter, which for the strongest winds gives us 40 lbs. per square foot. This result is arrived at thus: Let $A B = p$, the force of the wind (in fig. 2) in a direction parallel to the diameter, X Y, of the chimney. Resolving A B into its component parts at right angles, and with one of them, B D, as a normal to the curve at the point B, we have B D as the measure of force exerting pressure towards the centre of the chimney, and $B D = p \sin \angle ABD$. We have now to resolve this force again to get the component as measuring the effective pressure in a direction parallel with that of the wind, whence we have $p \sin^2 \angle ABD$. Taking a number of points affected by the wind, the mean sine of the arcs will be about ·75. The square of $·75 = ·56$, whence the mean effective pressure on the semicircumference $= p\ ·56$.

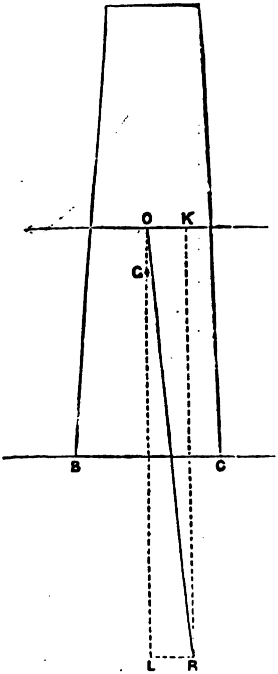
Fig. 2.



If the pressure on a square chimney be taken = 1·
that on an Hexagonal chimney may be taken = 0·75
,, Octagonal ,, ,, = 0·65
,, Circular ,, ,, = 0·5

Let S = the area in square feet of the vertical section through the middle of the portion of the chimney above the base or joint B C (fig. 3), then for a square chimney the total pressure P against the side $= p\,S$, and for a round and octagonal chimney $P = p\frac{S}{2}$. The resultant of this pressure may be considered to act in a horizontal line through O, the centre of gravity of the vertical diametral section. This centre of gravity may be found thus: let A B C D in fig. 4 represent the vertical section of a chimney or division of a chimney. Draw the diagonals B C and A D. On C B mark off C E = O B, and bisect A D in F. Join E F, then the point where E F cuts the centre line of the figure is the centre of gravity. Let H = the height of this centre O above the joint B C in fig. 3, then the moment of pressure is $H P = H p S$ for a square chimney, and $H\ P = \frac{H\ p\ S}{2}$ for a round or octagonal chimney, and to this moment of pressure *"the least moment of stability"* of the portion of the chimney above the joint or base B C should be equal. A balance of moments will exist when $H P = W\frac{B}{2}$, in

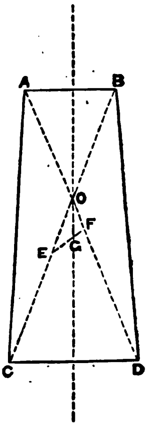
Fig. 3.



the case of a new chimney, or $H P = (W + B, \times 8000) \frac{B}{2}$ for an old chimney. To ensure stability, it is evident the moment of stability must exceed the overturning moment. In practice a factor of safety of 2 is sufficient to use, whence we have $H P \times 2 = W \frac{B}{2}$, or $(W + B, \times 8000) \frac{B}{2}$.

It is advisable to describe these forces graphically, as in fig. 3. Draw the vertical line O G L through the centre of gravity G of the chimney, or of the division above the joint in question, as may be required. Let O be the centre of pressure against the side. Set off O K equal to P and O L = W. Complete the parallelogram, and join O R then when the line O R crosses the base or joint B C at a distance of ¼ of B C from the centre O L, the chimney is sufficiently stable to prevent overturning.

Fig. 4.



It may be considered that the lines of resistance in a square and circular shaft of the same height are very nearly identical in shape and position when the diameter and sides of the square are respectively equal. This is in consequence of the round chimney, although containing less material, being subject to less pressure.

The manner in which a chimney yields to the pressure of the wind is, however, by the opening or cracking of one of the bed joints at the windward side, without completely overturning. This opening gradually extends, in a more or less regular zig-zag course diagonally downwards towards the lee side. The complete destruction eventually takes place, either by the shifting of the upper portion past its support below, or by the crushing of the brick-work at the lee side by the too great pressure concentrated there, or in many cases, from both causes acting together, and in all cases the upper portion of the chimney falls to pieces inside and out, filling the interior of the portion left standing.

The resistance to the horizontal shifting of a bed joint, is due to the friction of the horizontal faces of the blocks of stone or brick, and is called "frictional tenacity," whose amount at any given joint is the product of the vertical load on the joint into the coefficient of friction, which for masonry and brick-work with damp mortar, is about 0·74.

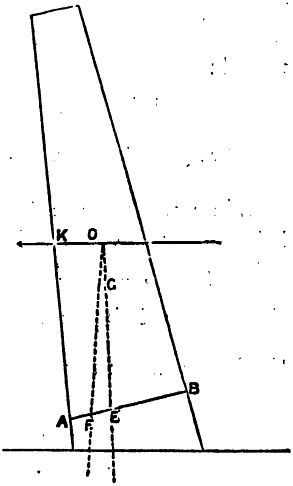
The tendency of the wind pressure being to open the bed joint at the windward side, and to crush the material at the leeward side, or to overturn the structure above the joint in a plane parallel with the direction of the wind, it is evident that the centre of resistance of the structure will be moved towards the lee side.

It has been found by experience necessary to limit this deviation of the centre of resistance from the centre of figure, so that the maximum intensity of pressure at the leeward edge shall not exceed twice the mean intensity. Denoting by q the ratio which the distance of this deviation bears to the diameter of the joint j, we have

for round chimneys $q = \frac{1}{4}$ the dia. of the joint.
for square „ $q = \frac{1}{6}$ „ „

The moment of stability of a chimney at any given bed joint is the product of the weight of the structure, or of the weight of the structure plus the tenacity of the mortar as the case may be, above that joint into the horizontal distance $q\,j$. If the axis of the chimney be vertical, as in fig. 3, the limiting distance $q\,j$, for the centre of pressure will be the same in all directions. But most chimneys are found to have their axes not quite vertical, and the least moment of stability is evidently that which resists the pressure in that direction towards which the axis of the chimney leans. In estimating the stability of existing chimneys this must be taken into account. In figure 5 let G be the centre of gravity of the structure above the joint $A\,B = j$, and let E be a point in the joint vertically below it, and let $q'\,j =$ the distance of the point E from the middle of the joint j, then the least moment of stability is denoted by $W \times E\,F = (q - q')\,W\,j$, F being the limiting position of the centre of resistance of the joint, all dimensions being in feet, and p being taken at 55 lbs. for new chimneys.

Fig. 5.



Then for round chimneys.

$$\frac{h\,p\,S}{2} - \left(\frac{1}{4} - q'\right) W\,j.$$

and for square chimneys

$$h\,p\,S = \left(\frac{1}{3} - q'\right) W\,j.$$

From these equations the following are deduced for practice. Let t = mean thickness of brickwork above the joint B C, w = the weight of 1 cubic foot of brickwork = 112 lbs. as a rule, d = mean outside diameter of chimney, then we have approximately—

$$\text{For round chimneys, } W = 3{\cdot}14\, wt. \left(\frac{d-t}{d}\right) S.$$

$$\text{For square chimneys, } W = 4 \quad wt. \left(\frac{d-t}{d}\right) S.$$

substituting these values in the equations just given, we have the following formula which will be found useful:—

$$\text{For round chimneys, } Hp = (1{\cdot}57 - 6{\cdot}28\, q')\, wt. \left(\frac{d-t}{d}\right) j.$$

$$\text{For square chimneys, } Hp = \left(\frac{4}{3} - 4\, q'\right) wt. \left(\frac{d-t}{d}\right) j.$$

When we require to know the mean thickness of brickwork for a new chimney, the form and dimensions being given, we have the following tentative formulæ, the results being multiplied by $\frac{d}{d-t}$ for the actual thickness, when t is so found.

$$t = \frac{Hp}{1{\cdot}57\, wj} \text{ for round chimneys.}$$

$$t = \frac{Hp}{\frac{4}{3} w j} \text{ for square chimneys.}$$

The outside diameter of the chimney at the ground line should not, as a rule, be less than $\frac{1}{10}$th the height. The batter varies from 1 in 60 to 1 in 10: 1 in 24 is very common.

A chimney shaft is made up of a series of steps or courses, one above the other. Each step is of uniform thickness, but as we ascend, each succeeding step is thinner than that which it rests upon, so that the bed joints between the steps, where the thickness changes, have less stability than the intermediate bed joints, and it is only these former to which it is necessary to apply the formulæ in determining the strength and stability of the structure.

The height of the different steps of uniform thickness varies greatly according to the judgment and practice of the architect or builder, and the custom in different districts.

If we take the safe load that can be borne by good brickwork, at 20,000 lbs. per square* foot, and the weight of brickwork with little mortar at the joints at 115 lbs. per cubic foot, we have 20,000 ÷ 115 = 170, approximately, as the extreme height in feet, we should make any single division, or length, of uniform thickness. This length is very seldom approached even in the tallest shafts, as the brickwork has also to bear the weight due to force of wind acting against the opposite side of chimney, in addition to the chimney itself. The steps, or courses, should not exceed 90 feet in height, except in cases where the chimney shaft is inside a tower which protects it from the wind. In chimneys from 90 to 120 ft. high, the lengths vary from 17 to 25 ft., the top height being 1 brick thick; in chimneys from 130 to 150 ft., the lengths are from 25 to 35 ft.; in chimneys from 150 to 200 ft. the lengths are from 35 to 50 ft. the top length being 1½ brick thick, and in very tall chimneys, that is, from 200 to 300 ft., and over, the lengths vary from 50 to 90 ft., the thickness of top length being 1½ bricks.

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* As the crushing strength of ordinary brickwork is much less than 90 tons to the square foot, the strength of the bricks used in very high structures should be ascertained by experiment.

The binding of the masonry* is often increased by laying at intervals hoop-irons, tarred and sanded, in the bed joints, the ends being turned down into the side joints. The length of the hoop-iron in each joint, should be twice the circumference of the chimney at that part.

Forge chimneys are often strengthened by strong bands of wrought iron, placed at intervals outside; but these are not necessary for boiler chimneys. Sometimes strong hoops about 3″ × ½″ are built in at intervals of 12 to 18 feet, to prevent cracks, but unless the chimney is provided with a very efficient lightning conductor, these masses of iron are apt to prove dangerous during a thunder-storm.

It is usual, and expedient, to protect the inside of the chimney with a lining of fire brick. For forge and ironworks' chimneys, where the gases escape at a very high temperature, the lining should be carried all the height. If care be taken to heat the chimney gradually for the first time of working, and subsequently, when it has been allowed to become cold, it is not necessary to have an air space between the firebrick lining and the shaft proper. In this case the lining may be included in the thickness of brickwork necessary for the strength and stability of the shaft. The firebrick lining may then be bonded into the other brickwork in the ordinary way, the thickness of the lining being ½ brick in the upper portion, and 1 brick in the lower portion, and should be laid in fire clay, and not in mortar like the other brickwork.

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* The bond usually adopted is 1 course of headers to 4 of stretchers. In circular chimneys a uniform bond for the outside course of brickwork is sometimes recklessly adopted.

In boiler chimneys it is, however, unnecessary to carry the lining all the way to the top. In small chimneys, under 100 feet high, it may be carried one-third, or one-half the way up, and in chimneys of great height, the lining need not be carried higher than from 50 to 80 feet, according to the height of the chimney shaft.

An arrangement often used, is to carry the lining up parallel, that is, without taper, and to let the outside shaft meet it at a very acute angle. This leaves an air space between the lining and the main body of the shaft, which should be provided with air holes, communicating with the external atmosphere, but carefully sealed from communication with the inside. This caution is necessary, because when the gases that pass through the flues have access to the air space round the lining, there is always a risk of damage being done by the explosion of inflammable mixtures of gas and air that may collect. It is, therefore, advisable, when an air space is provided, not to allow any communication between it and the inside flue, consequently the plan of leaving the air space open to flue at top, so often done, cannot be recommended.

It is, however, perhaps, best to dispense with the air space altogether, as the difference between the temperature of the portions of the chimney above and below the top of the air space, renders the masonry liable to fracture at this part, and many chimneys may be found so fractured without the actual cause being suspected.

In erecting a chimney, care should be taken that the building is not proceeded with too rapidly. It is sometimes restricted to a rate not exceeding 6 feet a day in height. It is advisable to build chimneys when the work can be most steadily proceeded with. When the structure is built up too rapidly, and the mortar has not time to set, a gale of wind is liable to press the chimney over to one side, where it stays—the compressible nature of the mortar offering little or no resistance. Consequently, the less mortar used the better. Cement, owing to its crumbling when exposed to a high temperature, cannot be recommended except for the top of the chimney, where it may, however, be usefully employed. Grouting should, as a rule, not be attempted.

In order to gain admission into flues and chimneys, many engineers and architects make doors in the sides or crown of the horizontal flues leading to the chimney. A much better plan, however, is to make an arched opening at the bottom of the chimney, or in the pedestal, at one side of, or opposite the flue entrance. This opening can be readily built up air tight. Such a provision in the chimney may be required for introducing a fire of wood and shavings, to cause the boiler fire to draw on first lighting up, after the flues have been allowed to become cold and damp, especially when they descend to the chimney. This opening would be of service when it is advisable to make experiments on the draught, which are too often overlooked, but which may be of great service in detecting a falling off in the draught, and lead to the detection of air leakages, and other defects that may operate strongly against the economical or efficient working of the boilers.

With respect to the best position for the dampers for regulating the draught, apart from all consideration of economy and efficiency, it is most convenient to have them at the end of the external flues of the boilers, or between the boiler and the chimney. The dampers are therefore generally so placed, but this is the least advantageous position for preserving the temperature in the flues and chimney, and the energy of the draught, which would be best preserved at meal-times and over night, by placing the damper on the top of the chimney. Here, however, it would not keep the flues under the boiler so warm as when placed in its usual position behind the boiler, and the effect would be felt in lighting up on Monday mornings.

Dampers at the ashpit might be used with some advantage in maintaining the temperature of the boiler flues.

The depth and area of the foundation will depend very much upon the nature of the ground upon which the chimney is built. In many cases where chimneys are built on the banks of a river, and other places where the upper strata are of alluvial clays, soft silts and made ground, it is necessary to go to a depth of 25 or 30 feet, or even more, to reach a good stiff clay, hard sand or rock. This depth below the surface is excavated and filled in with concrete in various ways, or piled, according to the practice of the locality, or judgment of the engineer, so as to economise material without risking unequal settling of the structure, which cannot be too carefully guarded against, as it has often led to the failure of the chimney.

CHAPTER III.

DESCRIPTIONS OF CHIMNEYS.

THE following account of some of the largest brick and stone chimneys that have been built may be of interest. The highest chimney is at Mr. Townshend's Works, Port Dundas, Glasgow; and it is, with the exception of the spire at Strasburg, the Great Pyramid, and the spire of St. Stephen's at Vienna, the loftiest building in the world. It is circular in section, and rises to a height of 454 feet from the ground. The foundations are laid 14 feet below the surface on a bed of stiff clay, mixed with pebbles, and consist first of six courses of hard brick on edge, covering a circular area of 47 feet in diameter, diminished by outward "scarcements" to a diameter of 44 ft. Over this solid substratum the foundation proper consists of twenty-six courses of brick also on edge, diminished by scarcements on both sides from 21′ 9″ to 8′ 6″ thick. At the surface the outside diameter is 32 ft., with walls 5′ 3″ thick (6½ bricks). There is an inside lining of firebrick carried up 50 feet, with an air space round it. At the cope the outside diameter is 12″ 8′, with 14 inch walls, the total height of the building being 468 feet. The thickness diminishes by half a brick every step. There are six steps; the first of 40 ft., then four of 80 ft., the top step being 94 ft. The outside batter is straight from bottom to top. The point of least stability is at top of second step from the ground.

In Glasgow there is also the celebrated chimney at the works of Messrs. Tennant and Co., St. Rollox. From the base of foundation to the top of chimney it measures 455½ feet. The section above ground consists of five steps,—54, 60, 96, 140 and 85 ft. in height. Commencing from the ground the thickness of wall at ground is four bricks; and diminishing half a brick at each step, being two bricks thick at top. The outside diameter at ground level is 40 feet, and at summit 13′ 6″. The point of least stability is at top of third step. The foundation is 50 feet square, and 20 feet deep. The inner chimney is a cylinder 16 feet diam., and 260 ft. high. It is not connected with the outer one, but nearly touches it at the top. The weight of the chimney is estimated to be about 7,000 tons.

In Halifax, at Messrs. Crossley's, Dean Clough Mills, there is a large octagonal chimney of stone. Its height when built was 381 feet, but some of the top was removed on account of the immense weight at the foundation. The width at the bottom is 30 ft. Nearly 10,000 tons of brick and stone were used in the erection, being considerably more than the weight of Messrs. Townshend's chimney in Glasgow.

The tall brick chimney at the Edinburgh Gas Works is 341½ feet from the bottom of the foundation. The shaft is circular, 264 feet high, and built in steps of 35, 40, 48, 58 and 83 ft., commencing from the base, which is 3½ bricks thick, the highest being 1½ bricks. The inside diameter of shaft is 20 ft. at base, and 11′ 4″ at top. The foundation and pedestal, which are square, are of stone, 77½ ft. high. The cost was nearly £5,000.

At Huddersfield there is a tall circular chimney at Messrs. Brooks's Fireclay Works. It measures from the foundation 321 ft., and rises 306 ft. clear above the ground. The base at the foundation is 36 ft. square. At the ground line it is 31 ft. and at the summit 11 ft. diameter. The flue is 14 ft. diam. at the bottom and 9 ft. at the top.

In Bradford, at Messrs. Mitchell Bros.' factory, there is an octagonal stone chimney, that rises 300 feet above the ground. The foundations consist of two courses of concrete 22 ft. and 21 ft. square by 12 inches thick each, resting upon the rock. It measures 20 ft. across at the foundation and 9 ft. at the summit.

At the West Cumberland Hæmatite Iron Works, there is a circular brick chimney, designed by Prof. Rankine, 251 feet above the ground, with 17 ft. foundation below. Inside diameter of basement is 18 ft. 10 in. Inside diameter of the four circular archways for flues, 7 ft. 6 in. Outside diameter at top of cone, 15 ft. 3 in., and 1½ brick thick; outside diam. at 2 ft. above bottom, 25 ft. 7 in.; outside diam. of square basement, 30 ft. × 30 ft.; outside dimensions of foundation course, 31 ft. 6 in.; outside dimensions of concrete, 34 ft. 6 in. sq. There are three steps, the two uppermost being 80 ft. each, whilst the bottom one is 88 ft. high. At summit the thickness is 1½ brick; at bottom of lowest step, 2 ft. above the ground, 2½ bricks, increasing by courses four bricks in order to spread the pressure. The cost was £1,560.

The well known chimney of the Shell Foundry at Woolwich Arsenal is 223 ft. 9 in. above the ground, with 16 ft. of brickwork below, making 239 ft. 9 in. above the bed of concrete. The base above the ground is 20 ft. square, with plinth and cornice, 27 ft. high, on which the octagonal shaft is erected. It is 16 ft. 9 in.

diam. at base, and 6 ft. 6 in. at top. The walls are 2 ft. 7½ in. thick at bottom of shaft, and are reduced by steps of 37½ ft. 4½ in., the top step of 26 ft. being 9 in. thick. The uppermost 9 ft. is bell-mouthed, and built in cement. The Portland stone cap weighs about 17 tons.

Perhaps the tallest *square* chimney in this country is that at the Camperdown Linen Works, near Dundee. This chimney, or rather tower, rises 282 feet from the ground. It is somewhat in the Italian style, and is built of variegated brick. At the summit of the tower, which is 230 ft. high, constructed in panels, there is a balcony, above which the shaft is octagonal. The thickness of the walls at the ground is 5 ft., at the balcony 2 ft. 6 in., and at the top 18 inches. This tower is quite distinct from the chimney proper, which is circular in form, 14 ft. 6 in. diam. at base, and 13 ft. 3 in. at top. Its thickness is 18 in. from ground to first panel; 14 in. from this to the balcony, and 9 in. from balcony to summit. The tower is 24 ft. 6 in. sq. at the ground, and 20 ft. sq. at the balcony, above which it tapers gradually to the summit. The weight is about 5,000 tons, and the cost is said to have been about £6,000.

At Messrs. Lister's, Manningham Mills, Bradford, there is a lofty square chimney, 249 ft. high, with panelled sides, and circular top. The inside of the square at ground is 10 ft., gradually increasing to 11 ft.

At Connah's Quay, Chester, there is another lofty square chimney, 245 feet high from the ground. The size inside is 17 ft. 6 in. at base, and 7 ft. at top. Its cost is said to have been but little over £2,000.

Besides the circular, octagonal, and square forms generally used, there are a few peculiar shapes sometimes met with.

With a view to get a parallel flue from bottom to top without using an inside shaft, the walls of a square chimney may be carried up in one thickness about 150 ft. high, and 14 inches thick. In order to obtain stability two buttresses are run up at each side, tapering to nothing at the summit. There is a chimney of this kind at the South Metropolitan Gas Works.

Some chimneys have been built, having a section like an eight-pointed star, the inside being octagonal or circular, with or without inside lining, or air space.

Iron chimneys are seldom used except for small boilers, and are usually of small dimensions, and made circular. A few, however, have been erected within the last ten years of considerable dimensions. There are two at the Creusot Works in France. One is 197 ft. high, 4 ft. 3 in. dia. at top, and 10 ft. at bottom. It is constructed with a hollow batter, and is firmly bolted to masonry work just clear of the ground. It was riveted together horizontally, and lifted into its place with a crane. The thickness of the plates is $\frac{3}{32}$ in. at top, and $\frac{7}{16}$ in. at bottom. Its weight is 28 tons.

There is a still larger chimney at Creusot, of which a description will be found in "Engineering," vol. xiii. It is 279 feet high, 7 ft. 6½ in. dia. at the top, 22 ft. 11½ in. at the bottom, and weighs 80 tons. It is built also with a hollow batter, and is held by bolts and a strong angle-iron ring, to a mass of masonry weighing about 300 tons. Its cost was about £1,600.

The experience in such chimneys is not yet sufficient to enable us to judge with any degree of certainty of their durability. It is, however, certain that with some kinds of fuel, in spite of careful painting and partial lining with brickwork, their destruction will be very rapid, and the adoption of iron chimneys can only be recommended where the cost of brick and stone precludes their adoption.

A brick or stone chimney, substantially built, and with a fair margin of stability, will last many generations, whilst an iron chimney of moderate thickness cannot be depended upon, in many cases, to last more than forty or fifty years.

THE SHAPE OF CHIMNEY TOPS.

Although the position and surroundings of the furnaces, with respect to the direction of the wind, have a very decided influence upon the draught, and may outweigh any small advantage that one chimney top may have over another, yet it must be admitted that the shape of the top has a perceptible influence in promoting or retarding the draught when a strong wind is blowing.

Some chimneys, which are not excessively wide, have a better draught in all high winds, which may be accounted for by the arrangement of the boiler-house, its surroundings producing a greater pressure of air at the furnaces when a gale is blowing. In some arrangements a gale from a certain quarter may have an exhausting action, tending to draw the air from the furnaces, whilst a gale from the opposite quarter tends to increase the pressure at the furnaces, and so improves the draught.

With a plain or "bluff" top, a strong wind may act partially as a damper, as may sometimes be seen by the action it has upon the column of smoke as it issues from the chimney. The wind not only flattens the escaping column, but it also tends to produce downward eddies, especially in very large chimneys. There is often evidence of the downward eddies on the outside in the blackened appearance of the masonry on the lee side of the chimney. But as the wind, striking against a bluff top tends to rise vertically in the first place, and clear the windward side of the chimney at a short distance above it, this shape is decidedly better than that of some of the tops so often seen, which are concave at the rim and convex at the orifice, and appear to be designed to guide the wind right into the chimney and check the draught. A better shape for an open top is concave towards the orifice, so as to give the wind an upward direction, whereby the tendency will be rather to promote than check the draught.

When there is both an inner and outer shaft, the design for deflecting the current of air upwards can be carried out to the greatest advantage. The top of the inner shaft should be stopped off a few feet below that of the outside shaft and surmounted by a concave deflecting cap, from which the currents of air admitted through suitable openings in the outer shaft are deflected upwards and not only prevent any downward eddying, but tend to induce an exhausting action in the inner shaft, and consequently to promote the draught. At the same time the top of the outside chimney should be surmounted with a concave deflecting cap.

It appears strange that in the endless variety of designs for chimney caps, in the case of a single shaft, advantage has never or very seldom been taken of the opportunity to make the cap hollow, and in such a manner as to cause an induced current upwards on the same principle as that just mentioned for a double shaft.

Some very shapely chimney caps are made concave below and convex above; were they made concave both above and below they would have the best form for splitting the current of wind, and so prevent it from interfering with the draught.

Covered tops of a pyramidal shape, having vertical, tapered openings at the corners, have been used with decided advantage. By this arrangement the wind can blow into only one or at most two of the openings at once, leaving the others free to discharge fully. The sum of the areas of the openings should in this case be considered as the size of the orifice of the chimney. When practicable, the openings should be so arranged that when the wind is blowing from the chimney to the furnaces, it does not tend to blow down any of the openings, or, in other words, one side of the top should face the furnaces when these are behind the chimney.

The cost of chimneys varies within very wide limits. A few years ago chimneys up to 90 feet high could be built in the Midland Counties in a certain style for £1 per foot, but a more usual cost is from £2 to £2 10*s.* per foot, for chimneys up to 100 feet high. As much as £22 a foot has been paid for some of the ornamental tall towers with inside shafts.

CHAPTER IV.

CHIMNEYS—LIGHTNING CONDUCTORS.

THERE are many engineers at the present time who argue that lightning conductors are useless, or even worse than useless; hence the number of tall chimneys seen unprovided with lightning rods in various parts of the country.

The destructive effects of lightning are much more frequent and ruinous than is generally supposed. Whilst some twenty cases could be quoted where lightning has fallen on unprotected powder magazines, and caused their explosion, killing thousands of people, and laying whole towns in ruins, it may be questioned whether a single case can be cited of a powder magazine being struck, that was properly protected by a lightning conductor.

The causes of the widespread disbelief in conductors as a means of preserving chimneys and other lofty buildings against the destructive action of lightning, are:—

1. The opinion commonly held, and often where we should least expect to find it, viz., that metallic bodies, especially when pointed, *attract* lightning, and are therefore dangerous. This opinion is probably due to the fact that during thunderstorms luminous points have often been seen on spires, vanes, ship's masts, and other elevated metallic bodies. The glowing appearance here spoken of is unattended by any heating effects, and is harmless.

This phenomenon, like some other effects of atmospheric electricity, is due to the highly charged electrical condition of the clouds and atmosphere, and it is at once concluded that these bodies have a superior attractive force for electricity over all others. Now metallic bodies, whether pointed or not, have no more power of *attracting or drawing* the lightning to them than non-metallic bodies, and it is the confusing of the apparent with the actual attractive force, or erroneously concluding that metals are good attracters because they are good conductors, that has brought about the misunderstanding on this point. Now in no case can it be said that the conductor attracts the lightning in the active and adverse sense which is here implied, and in which this term is often used. On the other hand, the conductor acts, especially when its top is pointed, in preventing the prominence to which it is applied from becoming highly electrified *by induction,* and in so much actually prevents the structure from attracting the cloud that electrifies it. On an electrified cloud passing over a pointed conductor, the opposite and induced electricity of the earth is discharged from the point of the conductor, and the cloud and air are often thereby neutralised without producing lightning at all. But when a discharge does take place the duty of the conductor is entirely passive: by offering a line of comparatively small resistance, it determines the direction of the discharge, which is not, however, in the first place brought about by the presence of the conductor, or, what more often happens, the presence of the uninsulated pointed conductor, by its peculiar property, prepares the resisting air in such a manner that the current of electricity is discharged quietly and without violence or a flash of lightning. Should, however, the electrified clouds be driven to the erection by the winds in such masses that the opposite kind of electricity does not stream away from the point of the conductor in sufficient quantities to prevent a spark from passing, the spark, or flash of lightning, will pass from the cloud to the conductor in preference to any neighbouring point, since the electric density will be greater here, and the resistance least. Hence the duty of the conductor may be considered as being entirely passive, as, by offering a line of comparatively small resistance, it determines the direction of the discharge when it becomes inevitable, although it is not brought about by the presence of the conductor in the first place, but by the action of the clouds and a large area of ground. To use an oft repeated simile, the conductor no more attracts the lightning than a water-spout, on the side of a house, attracts the rain from the clouds which it leads to the drain in the ground.

The fact that so many well-known buildings, which were repeatedly struck by lightning before being furnished with rods, have escaped being struck after the lightning rods were applied, would appear to be conclusive evidence of the passive character of the pointed conductor with respect to the discharge, and that its presence averts a violent explosion by rapidly neutralising the electrical condition of the atmosphere.

The luminous appearance, accompanied by a whizzing noise, sometimes observed when a very dense discharge is received by the conductor, is of a perfectly harmless character, and is probably of the same nature as the "glow" discharge, so well known to those who have made and witnessed electrical experiments.

2. The disbelief in the efficacy of lightning conductors is sometimes due to the carelessly expressed opinions of many writers on electricity, to the effect that thoroughly efficient lightning conductors might discharge the electricity *gradually* and harmlessly into the ground, but would be a poor protection to the building in the event of its being struck by a flash. Now, in answer to this, there are many cases on record of ships and buildings having been struck by lightning. Those provided with efficient conductors have borne the shock unharmed, whilst those unprotected have suffered severely. Perhaps the most convincing evidence of the efficiency of good lightning conductors is that adduced by Sir W. S. Harris from the journals of H. M. ships. In 1861, he writes, "We had between the years 1810 and 1815, that is, within about five years, no less than 40 sail of the line, 20 frigates and 12 sloops and corvettes, placed *hors de combat* by lightning. In 250 such cases, 100 seamen were killed and 250, at least, severely hurt. In the merchant navy, within a comparatively small number of years, no less than 34 ships, most of them large vessels, with valuable cargoes, have been totally destroyed, being either burnt or sunk, to say nothing of a host of vessels partially destroyed or severely damaged. Damage to H. M.'s ships by lightning has happily ceased (since effective conductors were applied); it is now not known in the British navy." Damage to ships by lightning seldom occurs now, as most ships are fitted with wire ropes, which act as lightning conductors.

3. A more reasonable objection, at first sight, to the use of conductors, is that many buildings have been damaged in spite of the presence of lightning rods,

and when it is assumed that a conductor acts by attracting the lightning, which would not take place but for the conductor's presence, the doubt at once arises whether the amount of security afforded by the rod really outweighs the danger provoked by its supposed active influence in attracting and bringing down a large flash of lightning. In all cases, where the matter has been properly investigated, it has been found that the conductors have been ignorantly and wrongly applied. Either the continuity of the conductor between its termination and the earth has been broken by the presence of rust at the joints, or by the iron connections under ground rusting away; by the rod itself being broken; or by the too common careless or ignorant mode of not bringing the end of the conductor properly to earth. It is the opinion of many that if the rod is merely buried a foot or two in the ground it is all that is required. We shall presently see this is by no means sufficient.

4. There is an opinion widely spread, and due in a great measure to the use of the terms "thunderbolt" and "electric fluid," by many writers on electricity, that a small rod of copper, from ½ inch to 1 inch diameter, is totally inadequate to carry off such a large quantity of "fluid" sufficiently rapidly and safely as is supposed to exist when a large flash of lightning is observed.

5. Many persons point to buildings, such as the dome of St. Paul's cathedral, as not being provided with any external special conductor, yet which have escaped being struck in very severe storms. In most of these cases, by the arrangement of the materials of which it is constructed, the building itself is a first-rate conductor, in some cases for a certain height only and in

others from the summit to the ground. St. Paul's is now fitted with copper rope conductors.

In applying a lightning conductor to a chimney or other similar structure, the principles to be kept in view are—

1. To use the best available material; that is, which acts best as a conductor of electricity, and resists corrosion. This material is copper.

2. To provide an adequate sectional area to lead the electricity harmlessly away. This is best arrived at by experience. Harris, in 1861, after citing a number of cases of terrific tropical thunderstorms, concludes that a copper rod $\frac{3}{4}$ in. diameter, or an equal quantity of copper under any other form, would resist the heating effect of any discharge of lightning which has yet come within the experience of mankind. Faraday considered a $\frac{1}{2}$ in. copper rod sufficient, but of course approved of using $\frac{5}{8}$ or $\frac{3}{4}$ in. rods when the expense was not too great.

3. It should be made in such a manner as to run the least risk of having its continuity interrupted in the event of its being fractured. With this object in view, rope is better than rods, since it can be made in the first place in one continuous length, whereby the risk of badly formed joints is avoided; it can be readily coiled and carried to its destination without being cut; and, in the event of being roughly used, the breakage of one or more strands does not destroy the efficiency of the remainder. When joints are used they should be formed by screwing the ends right and left-handed, and bringing them in close contact by a screwed copper socket of ample strength.

The conductor should be supported or suspended in such a manner as not to risk its fracture by settlement of the structure or disturbance of one or more of its supports or guides.

4. The upper extremity should project above the top of the chimney to a distance, say, equal to the diameter of the chimney top, and should terminate in a brush of three or four points arranged round the central terminal, and curved to project therefrom at an angle of about 45°.

5. As a rule the rod should be placed inside the structure in the case of a monument, where it is less liable to be damaged, and is in a better general position for protecting the building, besides being out of sight. But for a chimney the rod should always be outside, as the gases from some coals are liable to corrode copper and iron rapidly wherever they come in contact with these metals, especially in the presence of moisture.

6. To prevent lateral discharge the conductor should be in communication with all hoops or pieces of metal round the chimney, and the use of all insulated pieces of metal, especially arranged parallel to the conductor, should be avoided.

7. The rod should terminate in the ground in two or more branches, which should be carried into a well, and terminate in a large copper plate, or be connected with a water drain (made of metal, and not fireclay), or pump, water or gas pipes, or any other good conducting channel. Where this is not practicable, the several branches should be carried into earth that is permanently moist, and end in a cast-iron case filled with coke, or cinders; or have a large copper plate terminal; or where no moist earth exists permanently the branches under-

ground should have plenty of length, say 30 feet or more, according to the nature of the ground and size of rod. If no earth-plate is used, the wires of the copper rope should be unstranded and spread out.

When placed outside the chimney the rod may be brought down in contact with the stone or brick-work, and no insulating means are required. A flash ot lightning has sufficient intensity to break through miles of air in some cases, hence an attempt at insulation a few inches or even feet in length can have no practical effect in preventing it from striking the brick-work in case the rod should prove insufficient to carry it safely away.

The earth terminal of the rod—unlike the rod itself—should expose as much surface to the soil as possible, because this surface is the measure of the section of solid earth employed to carry off the discharge. Many authorities have advocated the use of a ball instead of a point at the top of the rod, the former being considered best for attracting the lightning from the building; a point is, however, far better for drawing off the electricity, as it does so quietly, and without sparks, and would commence its neutralising effect long before a ball would act, and by so doing might be the means of preventing a violent discharge altogether. In considering the advantages claimed for the ball top, it must not be forgotten that in comparison with the vast area of most electrified thunder clouds, the largest ball, the use of which could be contemplated, must be, after all, a mere point. Although many cases of fusion of copper points are recorded, this material should be still used in preference to iron for the points of conductors, although iron has a higher point of fusion.

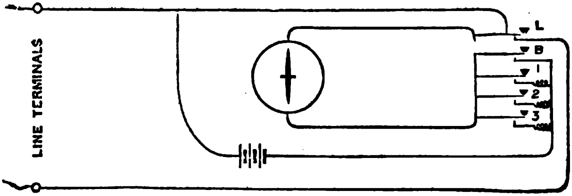
All combinations of copper and iron in contact should be avoided, especially when the smaller part of the combination is of iron, to avoid the rapid destruction of the iron by galvanic action, which is but too likely to occur; for instance, iron nails, spikes, staples, &c., should not be brought in contact with the copper rod to support it.

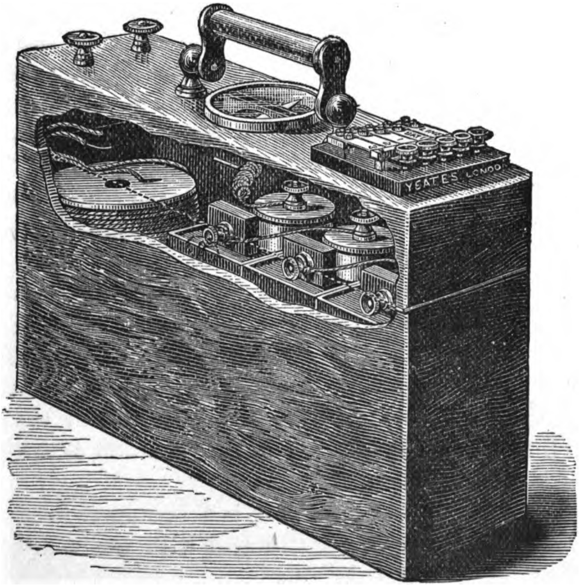
Notwithstanding that water or gas pipes of iron, placed a few feet from a conductor where it reaches the ground, have been broken by the lightning springing to them from the conductor, it yet appears to be the safest plan to connect the conductor with such pipes. In some cases the breakage has been doubtless due to explosion of the steam formed by the intense heat of the lightning current on meeting with the comparatively greater resistance of the ground between the conductor and the pipes. Where there is no resistance offered to the passage of the current no heat or violent effect will ensue.

In a previous paragraph we have spoken of the importance of terminating the rod in "good earth." Upon this depends the value of the lightning rod. Most of the accidents which have taken place—where conductors have been on the building—can be accounted for by insufficient earth connection. A lightning rod when fixed should be tested by a galvanometer, and the "earth" should be tested at least once a year.

A very portable galvanometer for testing lightning conductors has recently been introduced by Mr. Richard Anderson, M.S.T.E., F.C.S., of 101, Leadenhall Street, London.

The following woodcut shows the arrangement of the battery, galvanometer, and resistance coils. The battery consists of three cells, and is a modification of the old manganese cell, in which the carbon and oxide of manganese occupy the outer





and the zinc plate the inner or porous cell. By this arrangement (introduced a few years ago by Mr. H. Yeats, of Covent Garden), the surface of the negative element is greatly increased, and hence a more constant current is obtained, on account of the battery not polarising so rapidly as in the old form. Another advantage of this arrangement is that the cells can be almost entirely sealed up, the air openings being made within the porous cell. In the centre of the lid of the box is placed the galvanometer with a "tangent" scale. On the left are two terminals by which to connect the conductor to be examined. On the right-hand end of the lid are placed five keys, marked repectively, L, B, 1, 2, 3. Under B is one pole of the battery, so that by depressing this key, as will be seen by following the connections in the diagram, the battery current is sent through the galvanometer direct. If, however, we depress key No. 1, we connect the battery with the galvanometer through a known resistance. Key No. 2 has a larger resistance, and No. 3 still larger. The fifth key, L, closes the circuit within the limit of the instrument, but on being depressed opens it and includes the line or conductor placed between the two terminals at the other end. On pressing down L and B, it will be seen that the resistance of the line or conductor may be compared with the known resistance connected with any of the keys Nos. 1, 2, 3, or any of these resistances may be included with that of the line, so as to get a convenient deflection of the galvanometer needle.

In the case with the battery is a bobbin of insulated wire for connecting the instrument with the conductor and earth to be tested.

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